

# REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-04-

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<b>1. AGENCY USE ONLY (Leave blank)</b>		<b>2. REPORT DATE</b> 31 Aug. 03	<b>3. REPORT TYPE AND DATES COVERED</b> Final, 1 May 2001 - 30 Aug 2003	
<b>4. TITLE AND SUBTITLE</b>  Final report for F49620-01-1-0372 <i>Data Fusions with Communication Applications</i>			<b>5. FUNDING NUMBERS</b>  G F49620-01-1-0372	
<b>6. AUTHOR(S)</b> Professor Rick S. Blum				
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  Professor Rick S. Blum EECS department Packard Laboratory 19 Memorial Drive West Bethlehem, PA 18015			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>  AFOSR/NM 110 Duncan Avenue Room B115 Bolling AFB, DC 20332-8080			<b>10. SPONSORING / MONITORING AGENCY REPORT NUMBER</b>	
<b>11. SUPPLEMENTARY NOTES</b>				
<b>12a. DISTRIBUTION / AVAILABILITY STATEMENT</b>  <i>Approved for public release, distribution unlimited</i>				<b>12b. DISTRIBUTION CODE</b>
<b>13. ABSTRACT (Maximum 200 Words)</b> Data fusion ideas were employed to solve some important communication system problems. The first topic involves studying methods for generating and combining decisions from individual receivers in a multiple user scenario. The resulting theory of distributed multiuser detection or multiuser decision fusion has applications in both communications and in more classical problems of data fusion. In current digital cellular networks, for example, this theory is useful for combining decisions made at several remote base stations. This project focused on designing algorithms for and analyzing the performance and complexity of such schemes. The approach involved developing the theory for distributed multiuser detection by building on single user distributed detection theory, to which the PI has been a major contributor over the last few years. The second topic involved the study of methods employing multiple transmit and receive antennas (MIMO methods) to enhance performance. We developed new improved space-time codes and gave particular attention to the use of MIMO methods in a system (as opposed to a link which is interference free) which has not received much study.				
<b>14. SUBJECT TERMS</b> Distributed signal detection, multiuser detection, space-time codes, Antenna arrays, Multiple-input multiple output (MIMO) systems				<b>15. NUMBER OF PAGES</b>
				<b>16. PRICE CODE</b>
<b>17. SECURITY CLASSIFICATION OF REPORT</b> Unclassified	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b> Unclassified	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b> Unclassified	<b>20. LIMITATION OF ABSTRACT</b>	

Data Fusion with Communication Applications  
AFOSR grant F49620-01-1-0372  
Final Report (Submitted by Sept. 1, 2003)

Principal Investigator: Rick S. Blum  
Electrical Engineering and Computer Science Dept.  
Lehigh University  
19 Memorial Drive West  
Bethlehem, PA 18015-3084

## 1. Objectives

We believe the completed research is highly relevant to several of the technology areas identified under the Air Force Scientific Advisory Board's New World Vista Report. In particular, the completed research has provided contributions to Network Data Fusion for Global Awareness (listed under Global Awareness) and Communications (listed under Dynamic Planning and Execution Control). Data fusion has the potential to provide substantial quality and data rate gains in wireless and wired communication networks. At the beginning of this project, a number of topics remained uninvestigated which needed to be developed to advance these ideas. In this research we have developed some of these topics. One area of focus was on developing the topic of distributed multiuser detection. This included developing algorithms and analyzing their performance and complexity. Synchronous and asynchronous cases, short and long code cases, as well as binary and multiple-bit receiver decision cases were all considered for the parallel distributed detection topology using coherent receivers. A second topic of investigation involved the study of multiple antenna transmission and reception schemes which can be integrated into a system employing distributed multiuser detection. The research topics considered have led to research contributions to both the communications and data fusion community and these should produce improvements in future systems and products.

## 2. Executive Summary

Data fusion ideas were employed to solve some important communication system problems. The first topic involved studying methods for generating and combining decisions from individual receivers in a multiple user scenario. The resulting theory of distributed multiuser detection or multiuser decision fusion has applications in both communications and in more classical problems of data fusion. In current digital cellular networks, for example, this theory is useful for combining decisions made at several remote base stations. The techniques should also be important for future ad hoc networks. In these cases the network can employ multiple paths to transmit the same data so that diversity gain can be achieved. Each path may involve several hops of a wireless network. Even for communication over wires, combining the corresponding decisions of bits sent over different paths in a communication network is a promising idea to improve performance which should receive more attention. The actual combining may take place at the network level of the communication system which adds diversity at a level at which diversity is much less frequently employed. This type of diversity can also be used in conjunction with more traditional diversity methods. The completed research focused on designing algorithms for and analyzing the performance and complexity of such schemes. The approach involved developing the theory for distributed multiuser detection by building on single user distributed detection theory. Besides contributing

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to the area of communications, the proposed research on distributed multiuser detection is also applicable to a more general data fusion problem with structured interference. We note that several researchers have begun working on problems involving data fusion and communication since our research results appeared. In fact, we are told that this is now a very hot research topic.

The second topic investigated in this research project involved the study of methods employing multiple transmit and receive antennas to achieve impressive performance gains using space-time coding and related multiple-input multiple output (MIMO) methods. We developed new improved codes and gave particular attention to the use of MIMO in a system (as opposed to a link which is interference free) which had previously not received much study. However, we have indications that this also will become a hot research topic. Since our research results have appeared several research groups have begun working on this topic. Our investigations indicate that the resulting interference can have unexpected and interesting implications, which has attracted some attention.

### 3. Accomplishments

We have succeeded in generalizing the theory of distributed signal detection to multiuser cases and these results were just published in a journal article [1] (references in this section refer to the numbered publications in Section 5 of this report). In [1] we give a complete description of this theory of distributed multiuser detection and we describe the application to wireless communication systems. The application to wireless communication systems can lead to significant gains in real systems, as shown in [1], for only small increases in system complexity. On the other hand the theory of distributed multiuser detection advances the state of knowledge in the area of data fusion and should enable further theoretical and practical advances in the future.

We have developed an efficient and effective new methodology [2,3,4,5,10,15,16] for designing space-time convolutional and space-time block codes for quasistatic flat fading channels and rapid flat fading channels. The key idea is to consider more than just the worst case pairwise error probability which is the usual approach. We have devised an innovative new design criterion to augment the usual criterion. The augmented criterion averages over a few of the most important error events to substantially increase utility while maintaining simplicity. We present a particularly efficient method to check this new criterion which allows diversity gain performance to be checked at the same time, which is usually necessary, without additional computations. The resulting codes we have developed using this technique are, to the best of our knowledge, still the best existing space-time codes produced to date. Many other researchers have tried to develop theories to produce better codes but so far we have not seen any efforts that produced codes of the same complexity that provide significant improvement. Further the resulting design procedures are typically far more complex than what we have proposed.

While we have focused on flat fading cases in [2,3,4,15], we have also shown in [5] that the flat fading codes can be applied directly to the case of frequency selective fading channels by using OFDM. Further the performance achieved, see [5], is excellent. Overall a very low complexity approach is proposed in [5] that is shown to be very powerful. Still it may happen that a single carrier transmission approach is desired. Very recently [10,16] we have proposed a method for adapting our

flat fading code design procedure for frequency selective fading channels which does not require the use of OFDM. Here only a single carrier is needed. In [10,16] we also describe the general properties of space-time codes when they are applied to frequency selective fading channels. In particular, we provide theorems describing the change in performance of a particular space-time code when the frequency selectivity of the channel is changed in particular ways. We also describe the influence of correlation of the channel impulse response across space or time.

More recently, we were one of the very first research groups to study the effects of using antenna arrays in systems where users generally can interfere with one another. In particular we consider the use of space-time coding or what are more generally called multiple-input multiple-output (MIMO) approaches. In particular we have studied capacity optimum signaling [6,7,9,17,18,19] and shown that the optimum signaling can be significantly different from the cases where interference is not present. First consider the case assuming no channel state information at the transmitter, as considered in [6,7,17,18,19]. Assume an equal number of transmit and receive antennas are employed. If interference is not present then the optimum signaling sends an independent data stream from each antenna. When interference is present the number of independent streams should be reduced using a stream control algorithm. For asymptotically large interference only a single stream should be transmitted. For MIMO-OFDM systems [20] even more complicated behavior occurs since now MIMO is employed for each OFDM tone in an independent way. For large interference the interfering users should be allowed to use different tones to the greatest extent possible to avoid interference. In cases where some tones must be shared, due to a larger number of users, stream control must again be employed. We have also found the behavior with channel state information at the transmitter is very similar in [9]. We have also studied cases with quantization in the channel state information in [28] where we show the problem is very similar to a distributed detection problem.

A promising approach for reducing complexity while retaining a reasonably large fraction of the high potential data rate of a MIMO approach appears to be to employ some form of antenna selection [8,12,21,27]. Thus one can employ a reduced number of RF chains at the transmitter/receiver and attempt to optimally allocate each chain to one of a larger number of transmit/receive antennas. In this case only the best set of antennas is used, while the remaining antennas are not employed, thus reducing the number of required RF chains. We have studied [8,12,21,27] the optimum signaling for cases with antenna selection and we have shown that it is different from the optimum signaling for cases without selection, even if interference is not present. In particular we show [8,12,21,27] the optimum signaling is different for cases with weak SNR or SINR, but the same for large SNR or SINR. In fact the optimum signaling covariance matrix is generally a convex combination of an identity matrix (optimum without selection and interference) and a matrix with all identical entries (optimum with selection and weak SNR). Adaptive modulation is another promising approach to improve performance. We have shown [22,23] that considerable improvement is possible without complicated coding if the users are not moving too rapidly. If users do move rapidly, we have proposed [22,23] some robust approaches that still provide considerable improvement. We have also demonstrated [11] very recently the significant gains that can be achieved using a simple procedure to exploit multiuser



diversity in broadcast channels.

The ability to use wireless communication devices to form ad-hoc networks is one of the most powerful ideas to emerge over the last few years. Using ad-hoc networks to establish path diversity would allow decision fusion [1]. The actual combining may take place at the network level of the communication system which adds diversity at a level at which diversity is much less frequently employed. This type of diversity can also be used in conjunction with more traditional diversity methods. However, ad-hoc networks are still quite new and not so well understood. Recent research showed that the performance of an ad-hoc network can decay very unfavorably with size implying large networks may be impractical. Other research showed this may not be true if mobility is exploited and asymptotically large delay is allowed. In [13,24,25] we considered the impact of requiring a finite limit on the allowed delay. We show that for delays below a critical delay, unfavorable scaling occurs. However for delays above the critical delay, performance improves quickly. We also provide an upper bound on the delay-limited capacity and propose an approach that achieves this bound for asymptotically large networks.

We continue to consider the closely related topic of space-time adaptive processing (STAP) for the particular application of improved radar detection in [14,25]. The focus [25] recently has been on detecting range distributed targets, but an overall survey of our work in this area is scheduled to appear in [14].

#### 4. Personnel Supported

Rick S. Blum, (PI) Professor of EECS  
SUK C KIM, Post-doc  
Sigen Ye, Research Assistant  
Mu Qin, Research Assistant  
Zhenyu Tu, Research Assistant  
Pradeep Arkachar, Research Assistant  
Zhiyun Xue, Research Assistant  
Jinzhong Yang, Research Assistant

#### 5. Technical Publications

##### Journal Papers

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1. J. Hu and R. S. Blum,  
``Distributed signal detection for multiuser communication systems,``  
IEEE Transactions on Aerospace and Electronic Systems,  
pp. 1220-1229, Oct. 2002.
2. X. Lin and R. S. Blum, ``Systematic design of space-time  
codes employing multiple trellis coded modulation,``  
IEEE Transactions on Communications, pp. 608-615, April 2002.
3. R. S. Blum,  
``Analytical tools for the design of space-time convolutional codes,``  
IEEE Transactions on Communications, pp. 1593-1599, Oct. 2002.
4. Q. Yan and R. S. Blum,  
``Improved space-time convolutional codes for quasistatic slow fading  
channels,`` IEEE Transactions on Wireless  
Communications, Oct. 2002.

pp. 563-571, Oct. 2002.

5. R. S. Blum, Y. (Geoffrey) Li, J. H. Winters, and Q. Yan,  
"Improved Space-time coding for MIMO-OFDM Wireless Communications,"  
IEEE Trans. on Communications, pp. 1873-1878, Nov. 2001.

6. R. S. Blum, J. H. Winters and N. R. Sollenberger,  
"On the capacity of cellular systems with MIMO",  
IEEE Communications Letters, pp. 242-244, June 2002.

7. R. S. Blum, "MIMO Capacity with Interference", Journal  
on Selected Areas of Communications (Special issue on MIMO),  
pp. 793-801, June 2003.

8. R. S. Blum and J. H. Winters,  
"On Optimum MIMO with Antenna Selection",  
IEEE Communications Letters, pp. 322-324, Aug. 2002.

9. Sigen Ye and R. S. Blum, "System Capacity of MIMO  
Interference Systems with Feedback",  
to appear in IEEE Trans. on Signal Processing,  
Special issue on MIMO, Nov 2003.

10. Mu Qin and R. S. Blum,  
"Properties and trellis code designs  
of space-time codes for frequency selective channels",  
to appear in IEEE Transactions on Signal Processing.

11. Zhenyu Tu and R. S. Blum,  
"A simple approach to explore multi-user diversity for Gaussian  
vector broadcast channel," to appear in IEEE Communication Letters.

12. R. S. Blum, "MIMO Capacity with Antenna Selection and  
Interference", to appear in the European Journal on Applied  
Signal Processing (Special issue on MIMO).

13. E. Perevalov and R. S. Blum,  
"Delay Limited Capacity of Ad hoc Networks: Asymptotically  
Optimal Transmission and Relaying Strategy", submitted to  
IEEE Transactions on Communications, 2002.

14. Book chapter on "Robust Techniques in Space-Time Adaptive Processing",  
for the book "The Applications of Space-Time Adaptive Processing",  
IEE Publishers, 2003, Editor: R. Klemm, in preparation.

Conf. papers

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(was 11)

15. Q. Yan and R. S. Blum,  
"Robust space-time block coding for rapid fading channels",  
in the proceedings of GLOBECOM 2001, San Antonio, Tx, Nov. 2001.

16. Mu Qin and R. S. Blum,  
"Properties of space-time codes for frequency selective channels  
and trellis code designs",  
IEEE International Conference on Communications, Alaska, 2003.

17. R. S. Blum, J. H. Winters and N. R. Sollenberger,

``On the capacity of cellular systems with MIMO'',  
in the proceedings of the fall 2001  
IEEE Vehicular Technology Conference, Atlantic City, NJ, Oct. 2001.

18. R. S. Blum,  
``MIMO Capacity with Interference'', in the proceedings of the  
Conference on Information Science and Systems, March 2002.

19. R. S. Blum, "Analysis of MIMO Capacity with Interference",  
IEEE International Conference on Communications, Alaska, May 2003.

20. S. Ye and R. S. Blum, Optimum signaling of MIMO-OFDM systems with  
interference, in the proceedings of the XIth European Signal  
Processing Conference, Toulouse, France, Sept. 2002.

21. R. S. Blum, ``On Optimum MIMO with Antenna Selection'',  
in proceedings of the IEEE International Conference on  
Communications, N. Y., May 2002.

22. S. Ye, R. S. Blum, and L. J. Cimini,  
``Adaptive modulation for variable-rate OFDM Systems  
with imperfect channel information'' in proceedings of the  
Spring IEEE Vehicular Technology Conference, Birmingham, Al.  
May 2002.

23. Q. Su, L. J. Cimini, and R. S. Blum,  
``On the problem of channel mismatch in adaptive modulation  
for OFDM'' in proceedings of the Spring IEEE Vehicular Technology  
Conference, Birmingham, Al. May 2002.

24. E. Perevalov and R. S. Blum,  
"On the Delay Limited Capacity of Ad Hoc Networks",  
in the proceedings of GLOBECOM 2002, Taipei, Taiwan Nov. 2002.

25. E. Perevalov and R. S. Blum,  
"Delay Limited Capacity of Ad hoc Networks: Asymptotically  
Optimal Transmission and Relaying Strategy", in the proceedings  
of Infocom 2003.

26. K. F. McDonald and R. S. Blum, ``Performance  
Characterization of Space-Time Adaptive Processing Algorithms for  
Distributed Target Detection in Non-Ideal Environments''.  
IEEE Radar Conference, Long Beach, CA, pp. 298-303,  
April 2002.

27. R. S. Blum,  
``MIMO Capacity with Antenna Selection and Interference'',  
Invited paper at IEEE International Conference on Acoustics and Signal  
Processing, Hong Kong, 2003.

28. R. S. Blum, ``MIMO with limited feedback of channel state  
information'', IEEE International Conference on Acoustics and Signal  
Processing, Hong Kong, 2003.

## 6. Interactions/Transitions

### 6.1 Conference Presentations

A. Q. Yan and R. S. Blum,  
``Robust space-time block coding for rapid fading channels'',

GLOBECOM 2001, San Antonio, Tx, Nov. 2001.

B. R. S. Blum, J. H. Winters and N. R. Sollenberger,  
"On the capacity of cellular systems with MIMO",  
Fall 2001 IEEE Vehicular Technology Conference, Atlantic City, NJ, Oct. 2001.

C. R. S. Blum, "MIMO Capacity with Interference",  
Conference on Information Science and Systems, March 2002.

D. R. S. Blum, "On Optimum MIMO with Antenna Selection",  
IEEE International Conference on Communications, N. Y., May 2002.

E. S. Ye, R. S. Blum, and L. J. Cimini,  
"Adaptive modulation for variable-rate OFDM Systems  
with imperfect channel information"  
Spring IEEE Vehicular Technology Conference, Birmingham, Al.  
May 2002.

F. Q. Su, L. J. Cimini, and R. S. Blum,  
"On the problem of channel mismatch in adaptive modulation  
for OFDM" Spring IEEE Vehicular Technology Conference, Birmingham, Al.  
May 2002.

G. K. F. McDonald and R. S. Blum, "Performance  
Characterization of Space-Time Adaptive Processing Algorithms for  
Distributed Target Detection in Non-Ideal Environments".  
IEEE Radar Conference, Long Beach, CA, pp. 298-303,  
April 2002.

H. R. S. Blum, "Analysis of MIMO Capacity with Interference",  
IEEE International Conference on Communications, Alaska, May 2003.

I. S. Ye and R. S. Blum, Optimum signaling of MIMO-OFDM systems with  
interference, in the proceedings of the XIth European Signal  
Processing Conference, Toulouse, France, Sept. 2002.

J. E. Perevalov and R. S. Blum,  
"On the Delay Limited Capacity of Ad Hoc Networks",  
in the proceedings of GLOBECOM 2002, Taipei, Taiwan Nov. 2002.

K. E. Perevalov and R. S. Blum,  
"Delay Limited Capacity of Ad hoc Networks: Asymptotically  
Optimal Transmission and Relaying Strategy", in the proceedings  
of Infocom 2003.

L. Mu Qin and R. S. Blum,  
"Optimum space-time codes for frequency selective channels".  
IEEE International Conference on Communications, Alaska, 2003.

## 6.2 Transitions

The work from [10,22] of Section 5 was used at Mitre in a study:

Keith McDonald  
Signal Processing  
Sensors and Enabling Technology  
The MITRE Corporation  
Phone: (781) 271-7739  
Fax: (781) 271-7045  
kfmcd@mitre.org



Much of the space-time coding/MIMO work was used and further developed at AT&T Labs in NJ. The one difficulty with this transition is that many of the people doing this work have since left AT&T Labs. In fact the best contact person is now at the University of Delaware:

Len Cimini  
lcimini@optonline.net  
EE Dept., University of Delaware

7. Patent Disclosures  
None

8. Honors  
None